DESIGN OF A SINGLE SEGMENT CONDUCTANCE CATHETER FOR MEASUREMENT OF LEFT VENTRICULAR VOLUME

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Abstract- **The objective of this paper is to investigate how to best position the sensing electrodes on a single segment conductance catheter, and to calculate the expected performance. Using electrode potential data, obtained with the present five segment conductance catheter in pig experiments, we have interpolated the electrical field at any given point of time, and calculated what volume curve to expect with only two sensing electrodes.**

Comparison shows that the deviation between our calculated method and the present one is stable and small. Mean deviation with optimized electrode positions was 0.05% per sample, and the maximum deviation found for a single time sample was 2.57%.

This indicates that it is possible to build a thin single segment catheter with as good performance as for the present five segment conductance catheter.

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Keywords **- Left ventricular volume, conductance catheter, segment volume, pigs**

I. INTRODUCTION

The present methods measuring left ventricular (LV) volume, e.g. MRI, CT, angiography, 3D ultrasound and MUGA, do not meet the requirem ents of temporal resolution and accessability for an on-line registration. Although there are alternatives, e.g. the conductance catheter, metallic radiopaque markers, and sonomicrometry, they are not used in clinical practice because of their invasiveness [1-4].

One of the disadvantages with the present conductance catheter is its large diameter and rigidity, which could induce arrhythmias or worse damage. This is especially true when LV volume is reduced – as it often is in clinical practice.

To make the method more clinically feasible, without suffering from the arrhythmia problem, we have studied the possibility to make the catheter thinner and softer. To be able to perform that, multiple segments cannot be used due to the need for as many wires inside the catheter as electrodes used.

The objective of this study is to investigate how to best position the sensing electrodes on a conductance catheter with only one segment and what performance to expect in comparison to a state of the art five segment catheter. It has been shown that the mid-ventricular segments of the present conductance catheter is a fairly good correlate to the total volume obtained with the same method [5].

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We have studied recordings from a multi-segment catheter (Cordis Webster, Baldvin Park, Calif.), which measures conductance in five segments, which all are added to form a global volume as a function of time ($V_5(t)$). We obtained a continuous potential profile along the catheter through interpolation of the electrode potentials. In this way the potential difference between any two positions on the catheter can be estimated. The corresponding volume ($V_1(t)$) can also be computed. The optimal electrode positions can then be found through minimisation of the square error.

$$\sum_{t=t0}^{t1} \left(V_1(t) - V_5(t)\right)^2 \quad (1)$$

The minimisation is to be performed for all experimental conditions, for all experimental animals and for all available points of time.

II. METHODOLOGY

All the animals received human care in compliance with the European Convention on Animal Care. The study was approved by the Ethics Committee for Animal Research at Karolinska Institutet, Stockholm, Sweden.

A. Anaesthesia and surgical procedures

Pigs with a body weight of 38 to 43 kg were premedicated with intramuscular ketamine hydrochloride (20 mg/kg) and atropine sulfate (0.5 mg). Anesthesia was induced with intravenous sodium pentobarbital (15 mg/kg) and maintained by a continuous infusion of a ”cocktail” (0.30 ml/(kg*hour)) containing 2 mg fentanyl citrate, 25 mg midazolam, and 24 mg pancuronium bromide in a volume of 57 ml. The infusion was preceeded by a bolus of 0.15 ml/kg. The pigs were intubated and ventilated with a volume-cycled ventilator (Engström 300, Datex-Engström AB, Bromma, Sweden).

Catheters were inserted into the right femoral artery and vein for blood sampling, pressure monitoring, and drug and fluid administration. A catheter and a temperature probe were surgically introduced into the urinary bladder. An electrocardiogram was recorded by surface electrodes. A Swan-Ganz catheter (Baxter Healthcare Corp., Edwards Division, Santa Ana, Calif.) was placed in the pulmonary artery through the right external jugular vein for pressure monitoring, cardiac output measurements, and injections of hypertonic saline solution for parallell conductance calibrations.

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Abstract

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After median sternotomy , the pericardium was opened. A 5F transducer-tipped pressure catheter (Mikro-Tip, Millar Instruments Inc., Houston, Tex.) and a 7F, 12-pole conductance catheter (Cordis Webster, Baldvin Park, Calif.) with 7 or 9 mm spacing between the electrodes, depending on heart size, were introduced into the left ventricle through a stab wound in the apex. The tip of the conductance catheter was brought through the aortic valve. Proper position of the catheter was confirmed before each set of measurements by visual inspection of the individual segmental volume signals. The catheters were not repositioned once the experiment had started.

B. Data Acquisition

Hemodynamic data were acquired in apnea in end-expiration to minimise the effects of intrathoracic pressure variations.

The mechanical data were acquired during variable loaded beats by occluding the inferior vena cava for 10 to 15 seconds. To increase afterload, the descending thoracic aorta was clamped during a few beats. The second beat was the first beat exceeding initial left ventricular systolic pressure by more than 5 mmHg.

Every measurement was repeated at least three times, with a period of 2 minutes for circulatory stabilisation between acquisitions.

The conductance catheter was connected to a Leycom Sigma-5 signal-conditioner processor (CardioDynamics BV, Zoetermeer, The Netherlands). The principle and technique for volume measurement have been presented in detail [2, 6].

Sampling frequency was 200 to 250 Hz using an AD converting board (DAS-1601, Keithley Data Acquisition, Taunton, MA). Data were displayed on-line and stored on the computer hard disk.

All together, 234 measurements, each containing more than 3 heart beats, were made on 18 pigs, in both steady state and in extreme conditions (e.g. reduced preload, increased afterload).

C. Estimation of the electrical field through interpolation

The five segment conductance catheter is constructed with a number of electrodes, of which the most proximal and the most distal are current source electrodes, and the others in between are all sensing (measuring) electrodes. Global volume is then calculated from the formula

$$V(t) = \frac{1}{\alpha}\left(L^2 \cdot \rho \cdot \sum_{i=1}^{5} G_i(t) - V_c \right) \qquad (2)$$

where α is a dimensionless slope factor; L is the length between the measuring electrodes; $G_i(t)$ is measured conductance of segment i; ρ is the blood resistivity; and V_c is the parallel conductance from structures surrounding the left ventricle.

In our model the potential of electrode 1 (most distal sensing electrode) is arbitrarily set to zero. The next electrode (number 2) has the potential V1; that is, the potential difference of segment 1. Electrode 3 will at each sample have the potential V1 plus V2; that is, the potential difference of segment one plus two.

Similarly, the potentials of the other sensing electrodes are calculated. Assuming that the electric field is smooth, an interpolation (with cubic interpolation) will yield a potential profile along the catheter. These calculations must be done at each time sample. For a sampling rate of 200 Hz and 10 seconds of data sampling, 2000 potential profiles have to be computed. From these potential profiles, a volume signal can be calculated from two or more virtual electrodes.

Thus, our hypothetical single segment catheter consists of two current source electrodes, positioned exactly as on the 5 segment catheter, and two sensing electrodes, to be positioned somewhere in between.

D. Data analysis

A global volume curve was obtained by summing the inversed segmental voltages, as described. A potential profile was calculated for every sample of each measurement, giving us a 3-dimensional matrix with time, catheter position of the potential, and potential. The interpolation of the potential profile along the catheter length was done with 50 steps. That is: each segment was divided into ten equidistant steps, which gave 50 intervals defined by 51 positions.

The first virtual electrode (on the single-segmental catheter) was positioned at position 1, and the second at, for example position 11. Volume was then calculated at each sample using these positions of the electrodes, rendering a volume curve. The same was then made for each possible position of the virtual electrodes, for that particular measurement. All volume curves calculated was then scaled twice, giving them the same mean, maximum and minimum value as the global volume curve, and was then compared with the global volume curve, using a mean square error algorithm:

$$D(i) = \frac{\sum_i \left(\sqrt{(V_c(i) - V_b(i))^2} \cdot 100\right)}{I \cdot V_{mean}} \forall x1, x2 \qquad (3)$$

where D is the deviation per using the electrode positions x_1 and x_2; V_c is calculated volume (from potential profile); V_b is global volume; i is sample number, I is the number of samples; and V_{mean} is mean global volume; Hence, D is the

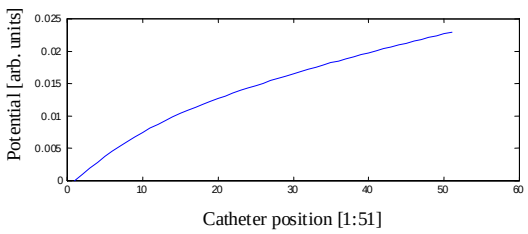


Fig. 1. Interpolation of the electric field along the catheter at one single time sample.

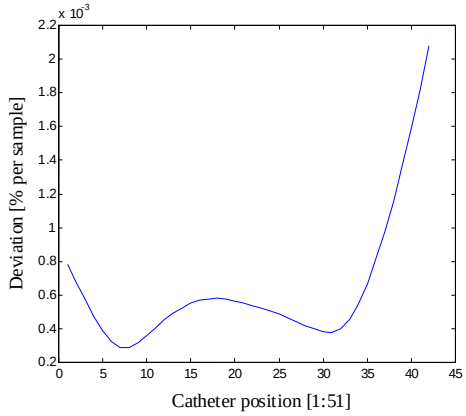


Fig. 2. With electrode 2 in a fixed position, the deviation may vary with the position of electrode 1 as shown in the figure. Occasionally, positions around 30 will be better, and the mean value will move towards a maximum. See text for details.

deviation per sample in percent of mean global volume.

These steps, i.e. calculation of volume at all possible electrode positions and volume deviation, were made for all 234 measurements. Each deviation calculation was then summed, and divided with the number of measurements, rendering a three-dimensional matrix with position of (virtual) electrode one, electrode two, and a mean volume deviation in percent for each pair of electrode positions. At the minimum volume deviation, the best electrode positions were found.

Another way to find the best electrode positions would be to, for each measurement, find the minimum volume deviation, and, amongst these, calculate the mean value of the positions. We might call this a horizontal approach to the problem, while the other (described above) is more of a vertical approach. The problem with the horizontal approach is (fig. 2) that for some cases the best positions for the electrodes, especially the most distal, have two minima. A mean position from two measurements would then be exactly in between, where we have a local maximum. Thus, in our case, the horizontal approach will be a way to find an almost worst case, and not the best.

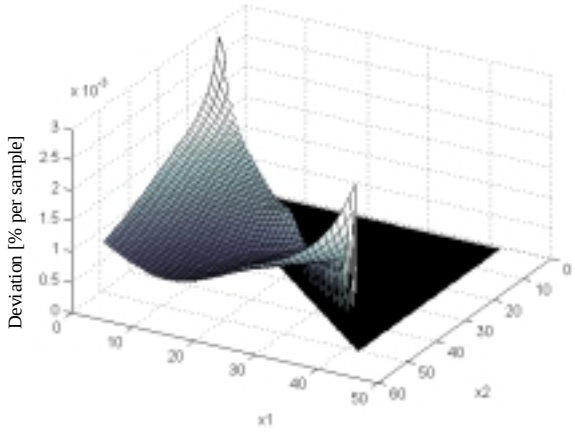


Fig. 3. 3D-plot of the deviation. x1 and x2 are positions of electrode 1 and 2, respectively.

III. Results

A. Mean deviation

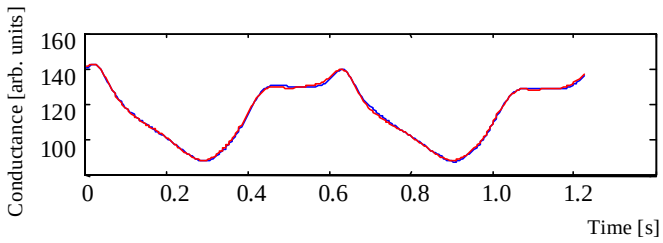
Fig. 3 shows a three-dimensional plot of the deviation in percent per time sample per measurement, including all measurements (i.e. steady state, preload reduction, afterload increase, infarction), with position of the virtual electrodes on the x- and y-axis. As can be seen, half of the plot is put to zero. This is due to the fact that electrode one, in the calculations, was not allowed to be more proximal than electrode two. If so, the calculations would have been made twice, resulting in an exact replica of the existing plot, but in reversed angle.

It is easily noticed that the 3D-plot has one minimum (deviation 0.05% per sample). This suggests that the best way to position the electrodes, in order to obtain a volume curve as similar as possible to those obtained with the 5-segmental catheter, is position 11 for (virtual) electrode 1, and position 51 for electrode 2. Thus, 4/5 of the whole length of the catheter should be used.

It is also noticed that the deviation is quite small, not only for the minimum, but for a number of positions surrounding the minimum. If we accept a slightly greater deviation (0.06% per sample), we will have a large number of positions to choose from.

B. Maximum deviation

As seen in fig. 4 and 5 the volume (or conductance) curves look almost identical for the optimised electrode positions.



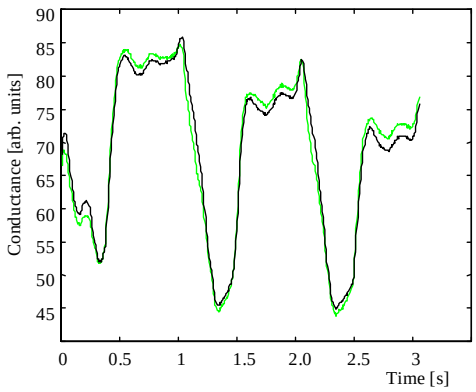


Fig.4 (upper) and fig 5 (lower). Both plots showing total conductance and calculated conductance. The deviation is hardly noticeable in fig 4.Fig. 5 is the worst registered case.

This holds for all loading conditions available, e.g. baseline, preload reduction, and afterload increase, although some slightly greater deviation may occur during fast changes in volume (maximum 2.57% in one preload reduction measurement).

IV. Discussion

We have chosen to refer to the difference between the calculated volume and the ”real” volume as “deviation”, and not “error”. As mentioned, there exists no reference method for the conductance catheter method. Hence, we can not know if the five segment catheter gives us the correct volume. And it has been shown that the slope factor α changes during the cardiac cycle, although it may be constant during systole [7-8]. Further, the calibration methods used (thermodilution and bolus of saline) are not exact. What we have is therefore a method that gives a somewhat correct (within limits of the calibration deviation) end-diastolic and end-systolic volume, and a somewhat correct volume curve, given that α is constant and all other assumptions are correct .

Of course, this is not the case. What we have done is to compare the standard way of obtaining left ventricular volume using the conductance method, with a somewhat simpler calculation method. The other parameters are still to be investigated.

As seen in the results, we believe that we have shown that it is possible to find the best positions of the electrodes for the single segment catheter, and also, which is as important, the positions do not have to be exact. Both sensing electrodes can be moved at least half a centimetre without affecting the result significantly. This is more important considering the clinical situation; both the ventricular size and the catheter position varies from case to case. But within certain limits, this does not matter. The next step is of course to show that all of this work in practice.

In all results, we have chosen to present the deviation in percent per sample. An other way could be percent per second, but when you look at on one of the parameters obtained from the pressure-volume loop, stroke work (which is equal to the loop area), a deviation calculated per second is not as accurate. The positive and negative deviations (i.e. calculated volume greater or less than global volume) will, in the loop area, add up and make the deviation less.

This is perhaps the most interesting field of use of the conductance catheter: an on-line registration of left ventricular volume integrated with pressure measurement to obtain pressure-volume. If volume and pressure could be measured simultaneously in a way that is clinically acceptable, a powerful tool for monitoring and diagnosis would be at hand [9].

V. Conclusion

With strategically placed electrodes it is possible to achieve the same performance for a single segment conductance catheter as from one with 5 segments in the porcine model. We believe that this also is the case for human subjects and intend to develop catheters for human use.

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